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Published in:
Proceedings from Indoor Air 2011

Publication date:
2011

Document Version
Accepted author manuscript, peer reviewed version

Link to publication from Aalborg University

Citation for published version (APA):
Frederiksen, M., Bergsøe, N. C., Kolarik, B., Spilak, M., Bekö, G., Gustavsen, S., Clausen, G., & Gunnarsen, L. (2011). Seasonal Variation in Monthly Average Air Change Rates Using Passive Tracer Gas Measurements. *Proceedings from Indoor Air 2011*. http://www.isiaq.org/news/indoor-air-2011-proceedings-now-available-on-a-flash-drive

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Seasonal Variation in Monthly Average Air Change Rates Using Passive Tracer Gas Measurements

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SUMMARY
Indoor air quality in dwellings is largely determined by the air change rate (ACR) and the magnitude of indoor air pollution sources. Concurrently, great efforts are made to make buildings energy efficient, which may result in low ACRs. In the present study, the monthly ACR averages were measured in five dwellings in Greater Copenhagen, Denmark. A passive tracer gas technique (Perfluorocarbon) was used to measure ACR in a seven-month period. Considerable differences were observed between the dwellings with monthly ACRs ranging from 0.21 to 1.75 h^{-1}. Only smaller seasonal variations, generally less than 30% of the overall average, were observed within the same dwellings, except during the warmest summer period, when ACR was generally higher. This suggests that a single measurement of the average ACR is a good indicator of the general situation, except for the summer period, and that varying driving forces for natural ventilation is partially compensated by changed occupant behaviour.

IMPLICATIONS
To the best of our knowledge this study is the first to examine the seasonal variation of air change rates in a full calendar year by using passive tracer gas techniques. Passive tracer gas techniques are particularly suitable for evaluation of ventilation-related indoor air quality in dwellings.

KEYWORDS
PFT, dwelling, ACR, indoor air quality, exposure

INTRODUCTION
Ventilation is an important parameter for indoor air quality (IAQ), and it is often a balance between sufficient ventilation to remove indoor pollutants and energy efficient operation of a building. The focus on energy efficiency has increased markedly since the early 1970s, while less attention has been paid to IAQ. Insufficient venting of indoor air pollutants such as bio-effluents, CO_2, chemicals or excessive moisture does not only influence the perception of IAQ, but may also be a concern for public health. The consequences of poor IAQ can range from decreased productivity to serious diseases. Since ventilation is a key parameter of IAQ, determination of air change rates (ACR) is important for generating reliable exposure estimates.

Typically, ACRs are measured using tracer gas. There are several strategies for introducing the tracer gas and conducting the measurement e.g. constant concentration method, constant emission method, decay method and also passive tracer gas method. The first of mentioned methods result in ACR with high time resolution, while the passive tracer gas method results in an average ACR over longer periods, typically days to weeks. The passive tracer gas method is simple to use in the field and only a minimum of training is needed in contrast the other methods requiring comprehensive equipment and extensive handling at the measurement site.

Driving forces for natural ventilation such as wind and temperature differences are strongest during winter. However, the discomfort caused by draught and cold together with the costs of heating, may reduce occupants' willingness to open windows etc. during cold periods. It is uncertain whether ambient driving forces compensate for changes in occupant behaviour.

Often ventilation rates are measured for shorter time periods, but the present study provides results of measurements of air change rates in five dwellings during seven successive one-month periods. Consequently, the study covers several seasons of the year (and will be continued to cover a full calendar year). The objective of the study was to investigate whether a single measurement of the monthly average ACR in a dwelling is a good indicator of the general ventilation conditions throughout the seasons. Furthermore, it will be investigated whether the driving forces for ventilation, which increase in cold periods, will be compensated for through the occupants' behaviour e.g. airing habits during warm periods.

METHODS

Five dwellings in the Greater Copenhagen area were selected for a one-year study of seasonal variation of monthly average ACRs. Dwellings with a minimum of scheduled renovation were prioritised; furthermore, one dwelling with known mould problems was included (dwelling C). The characteristics of the five dwellings can be seen in Table 1.

Table 1. Characteristics of the five dwellings included in the study.

	A	*B*	*C*	*D*	*E*
Type	Detached house	Detached house	Town house	Detached house	Apartment
Year of construction	1964	1921	2007	1947	2004
Area (m^2)	139	143*	98	101 (+101 basement)	85
No. of occupants	3	4	2	2	1
Mechanical ventilation	÷	÷	÷	÷	+
Tracer gas used	PMCH	PMCP	PMCP	PMCP	PMCH

PMCP: perfluoro methyl cyclopentane, PMCH: perfluoro methyl cyclohexane.
**An unoccupied basement is not included in the area.*

For the measurement of monthly ACRs, the so-called PFT technique (PerFluorocarbon Tracer) was applied. This technique was originally developed by Dietz and Cote (1982). In the present study, two types of tracer gases were used i.e. perfluoro methyl cyclopentane (PMCP) and perfluoro methyl cyclohexane (PMCH), however only one type in each dwelling. Hence, the dwellings were treated as single zones. In the dwellings 4-6 PFT sources were mounted along with 4-8 adsorption tube samplerss, depending on the size of the dwelling. The adsorption tube samplers were changed every month resulting in monthly ACR average. The amount of tracer adsorbed in the samplers was analysed using gas chromatography – electron capture detector (GC-ECD) and the ACR was calculated on the basis of the concentration, measured temperature and known emission rates, as well as the volume of the dwelling. Details of the PFT technique including analysis of tracer gases and estimation of tracer gas emission have been described earlier (Bergsøe, 1992; Leaderer et al., 1985). The uncertainty of single-zone PFT-measurements is less than 20%, though it may be higher if the tracer gas sources are not placed optimally.

Furthermore, CO_2 levels in bedrooms were measured using CARBOCAP® (GMW22, Vaisala, Finland) CO_2 monitors and logged every 5 minutes along with the temperature and relative humidity by U12-012 HOBO-loggers (Onset Computer Corp., USA). In addition, temperature and relative humidity was measured and logged every 5 minutes by HOBO-loggers mounted in the main rooms of each dwelling. The measurements presented here were conducted from late April 2010 to November 2010. The study will continue and complete 12 months of measurements, which will be presented at the conference Indoor Air 2011.

RESULTS

The monthly average ACR of the five dwellings ranged between 0.21 and 1.75 h^{-1} over a seven-month period. The seasonal variation was 2.3 times smaller than the inter-dwelling variation, resulting in a characteristic ACR for each dwelling (Figure 1).

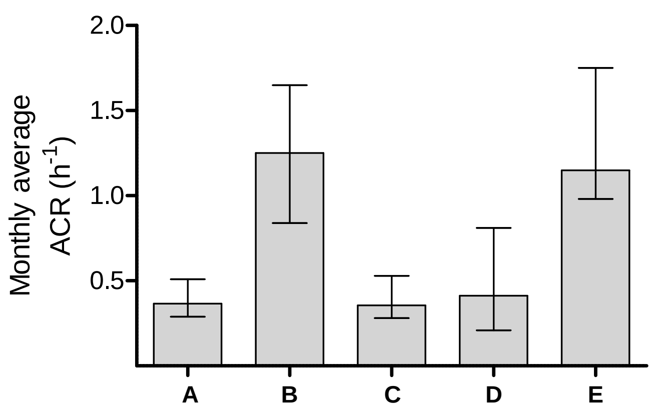

Figure 1. Mean and range of monthly average ACR in five dwellings (A-E) over a period of seven months (May to November, 2010).

The seasonal variation of ACR was relatively small (less than 30% of the annual average except for one measurement), except for the warmest summer period (monthly average outside temperature above 15°C) where the ACR was up to 96% higher than the overall average. For all five dwellings, the seasonal variation followed a similar pattern, which is likely to reflect the outside weather conditions (Figure 2). In general the monthly ACR average was higher during warm periods than during cold periods. Dwellings B and E stood out from the other three dwellings with fairly high ACRs. The monthly ACR average for dwellings B and E in the whole period was 1.25 and 1.15 h^{-1}, respectively; the overall average of the three other dwellings was 0.38 h^{-1}.

CO_2 levels were monitored in the bedrooms of the dwellings. In many cases high CO_2 levels were reached regularly during the measurement periods. Table 2 shows the maximum CO_2 level during the period in one of the bedrooms for each dwelling.

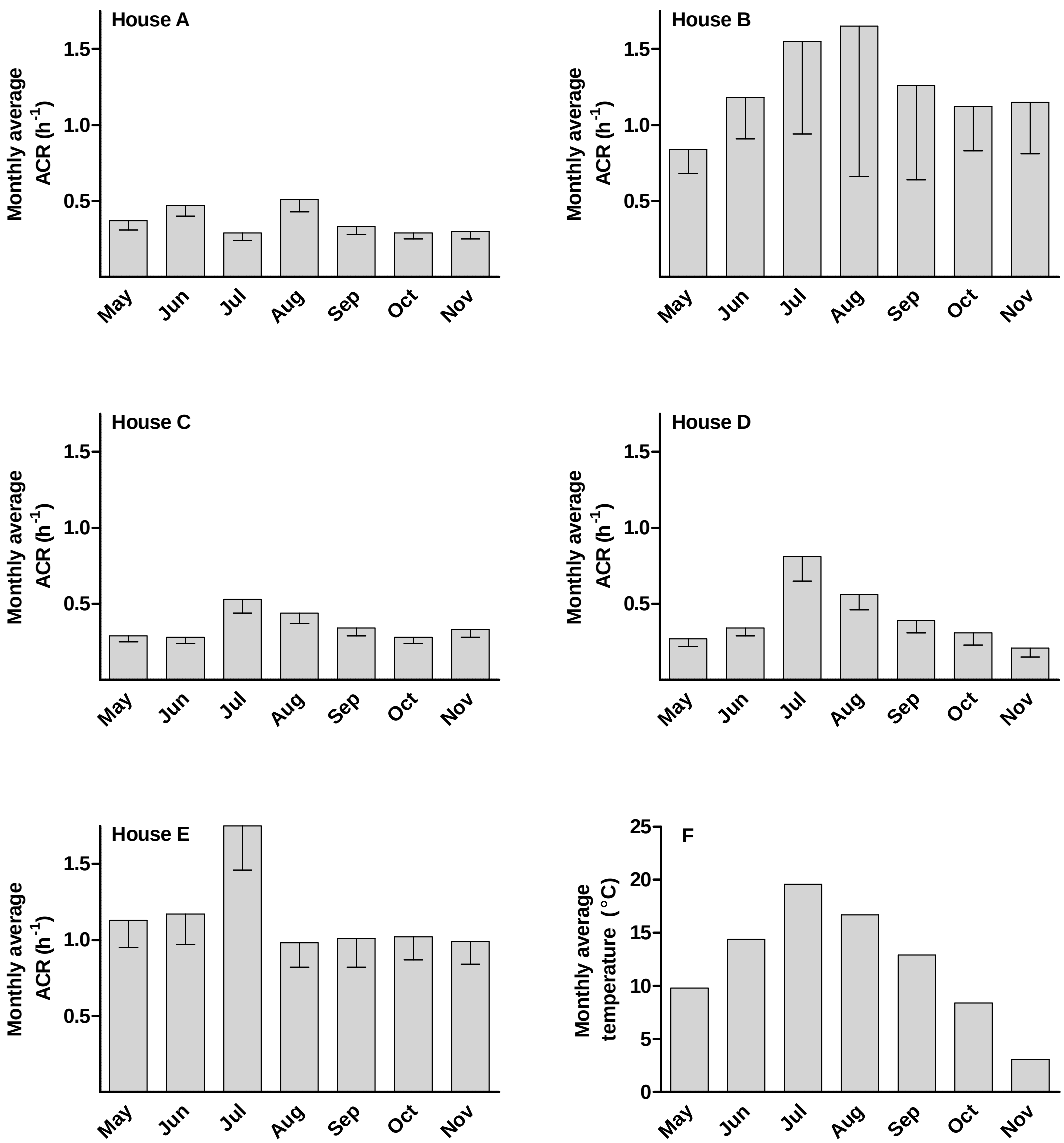

Figure 2. Seasonal variation (May to November) of the monthly ACR average in five dwellings (A-E). The error bars indicate the standard deviation of the adsorption tubes included in the determination of the monthly ACR average. F) Monthly average temperatures in Copenhagen (DMI, 2011).

Table 2. Maximum CO_2 levels, room volume and number of occupants usually present in bedrooms* in the five dwellings.

	A	*B*	*C*	*D*	*E*
Max. CO_2-level (ppm)	4990	3270	3210	4430	1910
Bedroom volume (m^3)	30	36	28	32	31
No. of occupants in bedroom	2	2	2	1	1

**If more than one bedroom, one adult bedroom was selected.*

DISCUSSION

The seasonal variation of ACR was found to be relatively small, with the exception of the warmest summer months. However, large inter-dwelling variation was observed. This indicates that a single measure of the monthly ACR average is a good measure of the general ACR found in a specific dwelling in Denmark. The dwellings included in the present study represent a variety of building types, which may partly explain the observed variation. For dwellings B and E very high ACRs were measured, but these are likely to be caused by two different issues: Dwelling B is an old villa from 1921 with a wood-burning stove, which is known to increase natural ventilation. All the dwellings were treated as single zone, but dwelling B had two stories. The results showed that these were not completely mixed, thus a larger uncertainty was related to the measurements in dwelling B (Figure 2). Dwelling E, on the other hand, is a recently built apartment. In this case it was expected that a large proportion of the incoming air was air from other apartments or hallways rather than outdoor air. This contribution will be investigated further in the future. Dwelling E was also the only dwelling with a mechanical ventilation system.

Dwellings A, C and D all had relatively low ACRs and in some periods the ACR was so low that it may be critical with regards to obtaining sufficient removal of pollutants in the indoor air. The average ACR of 0.38 h^{-1} for these three dwellings is somewhat lower than the minimum requirement for new dwellings as stipulated in the Danish Building Regulations corresponding to 0.5 h^{-1} (SBI, 2010).
Preliminary comparison, by simple linear regression, of the overall ACR for each dwelling with the maximum CO_2 level measured indicated the expected lower maximum CO_2 at higher ventilation rates. However, the correlation was not statistically significant ($p=0.2$). The CO_2 level is also influenced by open/closed internal doors and not only determined by external ACR. Inter-zonal airflows have been discussed in more detail by Gustavsen et al. (2011).

In the present study the period of averaging is relatively long. The drawback of this could be that prolonged periods, when the occupants are absent, are included in the average, resulting in a too low ACR. On the other hand, if occupants are present, a long period of averaging will give a good indication of the general situation, and possibly give a better estimate of the general exposure situation.

The PFT technique has many advantages as it is simple to apply in the field and robust enough to be sent by regular post. Furthermore, it can be used over a wide range of time spans, and since it is based on passive emission and sampling, it works silently, takes up very little space and is virtually invisible when installed. The drawbacks of the method include a systematic underestimation of ACR when ACR varies in the measurement period. Leaderer et al. (1985) have estimated the bias to be 3-6%, whereas Sherman (1989) modelled that it may result in a negative bias of 15-20% in homes. Sherman also concluded that the passive tracer gas technique results in “effective ventilation rates”, which better represents the situation for pollutants present in indoor air. This means that if there is a bias, it will be the same for indoor pollutants (with constant emission). Finally, the perfluorocarbon gases are assumed not to adsorb to common surfaces in typical dwellings. It is possible that some adsorption may occur in dwellings with a high ‘fleece-effect’. Such type of adsorption would result in overestimation of the ACR. Only few studies have investigated the effect of fleecy surfaces in dwellings. One study found that the ‘fleece-effect’ caused the PFTs to overestimate the ACR by 24-39% in a single dwelling with large fleecy surface areas (Gunnarsen et al., unpublished). The result of the ‘fleece-effect’ is likely to be highly dependent on the surfaces present in the dwelling as well as the vapour pressure of the applied tracer gas. The extent of the fleece-effect in the present test-dwellings will be investigated further in the future by comparing PFT measurements with CO_2 decay and the constant concentration method (preliminary results presented by Bekö et al. (2011)).

CONCLUSIONS

Overall, the monthly ACR average varied less than expected and the results suggest that a single measurement is a good indicator of general ventilation conditions with the exception of the warmest summer months, though a larger study is needed to confirm this. This indicates that the driving forces for natural ventilation to a large extent compensates for altered occupant behaviour during the cold periods.

ACKNOWLEDGEMENT

The home-owners in the study are gratefully acknowledged for their participation in the project. The study was performed as a part of CISBO (Centre for Indoor air and Health in Dwellings), which is funded by RealDania.

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